Geomorphology and Morphogenesis of the Non-siliceous, Non-aqueous Fluvial Systems of Titan: A Review

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***Abstract*-Titan is the only moon known in the solar system to possess not only an atmosphere, but an active weather cycle, tectonics, and erosive geomorphology. This weather cycle involves primarily liquid alkanes of methane and ethane (along with photochemical alterations of said compounds). Such liquid alkanes are the constituents through which stable bodies of liquid have been observed on Titan. These bodies undergo fluvial processes, among others. The aim of this review is to collate and assert the general consensus on Titan's fluvial geomorphology and morphogenesis through a holistic and comprehensive analysis of the current research paradigm. It is noted that Titan possesses fluvial morphologies similar to those found on Earth and Mars but under differing parameters, however, there are also a great number of differences which are of great importance to both present and future research. It is also important to note that Titan operates on a different temperature and chemical regime, along with a lower gravity and higher atmospheric density than Earth.**

***Keywords*-Titan, fluvial, methane, geomorphology, review.**

I. Introduction

It is well known that there are celestial bodies beyond Earth which possess fluvial geomorphology, namely Mars (Squyres, 1988), and Titan (Devon M. Burr, Fluvial features on Titan: Insights from morphology and modeling, 2013), whereas Earth and Mars utilise water in their fluvial processes (both extinct and extant) and geomorphology (Squyres, 1988), Titan undergoes similar processes using liquid alkanes (E. R. Stofan, 2007) and organic compounds (Birch, Hayes, Howard, Moore, & Radebaugh, 2016). Furthermore, in place of silicon, Titan possesses water ice as its primary constituent for surface rock (Collins, Pollito, Litwins, & Sklar, 2011). This review aimed to collate the current consensus on the morphogenesis and geomorphology of Titan's fluvial systems, along with providing specific sections of collation for particular regions and morphologies of interest (as outlined in the main body). This review did not aim to discuss research regarding cryovolcanism on Titan (although it will be mentioned in some sections), nor did it cover research into Titan's meteorology and pluvial processes, but they were studied to the degree that they would pertain to Titan's fluvial geomorphology. Furthermore, while directly relevant, there was limited coverage of lacustrine morphogenesis and geomorphology as it is not in the scope of this review.

The majority of data in the featured research articles was collected by Cassini's synthetic aperture radar (hitherto referred to as SAR) (National Aeronautics and Space Administration (NASA), 2018), visual and infrared mapping spectrometer (VIMS) (National Aeronautics and Space Administration (NASA), 2018), and Huygens' descent imager/spectral radiometer (DISR) (European Space Agency (ESA), 2019), where relevant other instruments will be mentioned. At present there are few data available to researchers regarding Titan's fluvial processes owing to only one spacecraft (the NASA, ESA, and ASI joint venture Cassini-Huygens) that has orbited and landed upon Titan. Moreover, Titan's thick atmospheric haze limits our ability to analyse the surface of Titan outside of the infrared band (M. G. Tomasko, 2005) and prevents detailed analysis of Titan's surface from orbit. As such, there have been a limited number of detailed studies pertaining to the fluvial geomorphology of Titan, the aim of this review was to aggregate these studies into a comprehensive consensus in order to facilitate discussion about the future of research regarding Titan's fluvial systems. Such a consensus will be of use for when the next generation of spacecraft bound for Titan will arrive. Principally of note is NASA's Dragonfly rotorcraft, the primary aims of the vehicle are to study Titan's prebiotic chemistry and the interaction between Titan's equatorial dunes and the methane cycle, however, analyses of Titan's fluvial geomorphology are expected to take place (James W. Barnes, Science Goals and Objectives for the Dragonfly Titan Rotorcraft Relocatable Lander, 2021). Dragonfly is expected to launch in 2027 and arrive at Titan in 2034 (Talbert, 2020). Additionally, there is need to provide some definitions, with this in mind: aeolian pertains to any observation produced or influenced by wind, fluvial pertains to river, pluvial pertains to rain, and lacustrine pertains to lakes. Moreover, morphogenesis is the origin of geologic features, silicious pertains to the element silicon and aqueous pertains to water.

II. Titanian Fluvial Geomorphology: General Insights

The surface of Titan is marked by a plethora of geomorphological features, of which, fluvial features make-up approximately as little as 10% (Devon M. Burr, Fluvial features on Titan: Insights from morphology and modeling, 2013), to as much as 20% (M. H. Langans, 2012) of Titan's surface area. The majority of fluvial features on Titan consist of what is regularly referred to as "channels" (Ralph D. Lorenz e. a., 2008) (Devon M. Burr, Fluvial features on Titan: Insights from morphology and modeling, 2013) (C. D. Neish, 2016) (J. Radebaugh, Regional geomorphology and history of Titan's Xanadu province, 2011) (Birch, Hayes, Howard, Moore, & Radebaugh, 2016), these channels typically appear in one of two classifications, those being 'radar-bright' and 'radar-dark', in reference to their radar albedo, with brighter channels being more reflective (M. H. Langans, 2012). Typically, coarse material sitting at the bottom of the channel is believed to be the cause of this reflectivity, indeed, (M. H. Langans, 2012) notes that coarse material being deposited at the bottom of a channel is the usual cause for such reflectivity. Lower albedo mappings of channels are typically indicative of smoother sediments (M. H. Langans, 2012) (Devon M. Burr, Fluvial features on Titan: Insights from morphology and modeling, 2013) or the flow of liquid alkanes (V. Poggiali, 2016) in active or semi-active river systems. As for why coarse sediment appears brighter, it is theorised that sediments with diameters greater than the 21.7mm wavelength of the SAR will be unable to reliably absorb radar emissions and as such will present as being highly reflective (Devon M. Burr, Fluvial features on Titan: Insights from morphology and modeling, 2013).

The fluvial channels seen on Titan are deeply incised (Devon M. Burr, Fluvial features on Titan: Insights from morphology and modeling, 2013) (Ralph D. Lorenz e. a., 2008), implying that the surrounding bedrock has been softened by some surface process (M. H. Langans, 2012), (M. H. Langans, 2012) argues that this is due to tectonic processes which in turn lead to the rectangular networks seen on Titan due to structural control. Particularly, extensional tectonics is the predominant tectonic mechanism producing these effects (Burr, Drummond, Cartwright, Black, & Peron, 2013). (Burr, Drummond, Cartwright, Black, & Peron, 2013) note that 50% of the observed networks in the SAR data are rectangular, with a further 8% being parallel and another 27% being dendritic. This further reinforces the notion that Titan's fluvial landscape selection is driven primarily by tectonic processes. Rectangular networks are noted by (Howard, 1967) to be caused by joint control.

The morphology observed in Titan's fluvial networks is of great diversity, driven significantly by the aforementioned presence of tectonic activity, but also by factors such as latitude. Towards the poles, Titan tends towards a more humid environment (J. W. Miller, 2021), this humidity, consisting primarily of methane, leads to persistent methane precipitation, which is the main driver of Titan's fluvial morphogenesis (M. H. Langans, 2012). This is further reinforced by the absence of observed fluvial features produced by sapping, (M. H. Langans, 2012) notes that only two sapping network structures have been found thus far, one near the Huygens landing site due to DISR data, and the other due to Cassini SAR mapping, with (M. H. Langans, 2012) noting that another set of networks is similar to networks found in the Floridian panhandle (S.A. Schumm, 1995). It is important to note that sapping features, along with deeper valleys, are indicators of, as (E. R. Stofan, 2007) puts it, "methanifers", of which, bar the sapping features, are yet to be found on Titan (M. H. Langans, 2012). (M. H. Langans, 2012) also notes that it is unlikely that any networks on Titan have been formed through sapping alone as this has not yet been shown on Earth or on Mars. This is not to say that “methanifers” do not exist, (M. H. Langans, 2012) and (Jeffrey M. Moore, 2010) note that various features (primarily the shorter fluvial structures surrounding Titan’s seas, the southern lacustrine regions and the “stubbier” fluvial networks observed at the proximity to the Huygens landing site (Burr, Drummond, Cartwright, Black, & Peron, 2013) (M. H. Langans, 2012) (Jeffrey M. Moore, 2010) (Laurence A. Soderblom, 2007)) likely require the presence of “methanifers in order for them to form.

(E. V. Bohacek, 2023) notes that it may be possible for liquid methane that has the potential to intrude into the porous ice rock on Titan and form clethra, these may in turn be the source of the “methanifers”, (E. V. Bohacek, 2023) goes on to state that the abundance of methane on the surface of Titan runs country to this notion.

Whereas rectangular networks are produced via a combination of precipitation and structural control on Titan, dendritic networks are not typically formed via structural control, instead relying on slope gradients as the driver for precipitation runoff (Burr, Drummond, Cartwright, Black, & Peron, 2013). The dendritic networks on Titan tend to be present further towards the poles, where there is both a greater quantity of humidity and rugged terrain (Burr, Drummond, Cartwright, Black, & Peron, 2013) (M. H. Langans, 2012), this rugged terrain allows for strong quantities of orographic rainfall, which in turn is the primary decider for the locality of pluvial activity at a given latitude (M. H. Langans, 2012). This notion is further reinforced by presence of dendritic networks closer to the equator which are in the vicinity of rugged terrain, particularly this is observed around western Xanadu (due in part to precipitation travelling west-east and thus leaving more structurally controlled networks in the “Middle Rugged Terrain” and “Eastern Belts”) (J. Radebaugh, Regional geomorphology and history of Titan’s Xanadu province, 2011) (Devon M. Burr, Fluvial network analysis on Titan: Evidence for subsurface structures and west-to-east wind flow, southwestern Xanadu, 20009), and the mid-latitudes (A. Le Gall, 2010). Not only are these networks dendritic, but they are radar-bright, which is indicative of them not undergoing pluvial modification in the present. Indeed, there are several reasons to explain the paucity in active fluvial systems beyond the Titanian poles. One of the more prevalent concepts is that of infrequent rainstorms being the lead source of liquid alkanes to these more equatorial regions (C. D. Neish, 2016) (Burr, Drummond, Cartwright, Black, & Peron, 2013) (M. H. Langans, 2012) (Birch, Hayes, Howard, Moore, & Radebaugh, 2016) (Ralph D. Lorenz e. a., 2008). (Ralph D. Lorenz C. A., 2005) notes that these storms occur at a frequency on the order of once every 10^3 years. Another theory is that ancient Titan was more humid, either due to a generally larger abundance of methane (M. H. Langans, 2012) or has been periodically resupplied by tectonic outgassing and thus has been subsequently photochemically withdrawn (Giuseppe Mitri, 2007). This hypothesis is coupled with the possibility that the lower latitudes merely receive mild “drizzle” which would allow for little active fluvial modification (Tetsuya Tokano, 2006) (M. H. Langans, 2012).

With this in mind, it is important to note that the inactive mid-latitude channels resemble terrestrial wadis, merely on a much larger scale, these Titanian wadis are the byproduct of Titan’s general methanogenic aridity (M. H. Langans, 2012) (Ralph D. Lorenz e. a., 2008), and are also similar to Martian outflow channels (M. H. Langans, 2012).

As (E. V. Bohacek, 2023) notes that due to the aforementioned photolysis, ethane is a common constituent in the seas and lakes of Titan. Moreover, due to ethane’s higher boiling point may cause it to evaporate from springs (likely produced by the aforementioned “methanifers” erupting onto the surface) and precipitate in the lower courses of active river systems. This leads the upper courses to be dominated by methane precipitation. In turn, due to the differences in fluid mechanics between ethane and methane, (E. V. Bohacek, 2023) notes that this may impact Titan’s fluvial dynamics.

III. Regional Fluvial Geomorphology

The aim of this section is to analyse general properties of certain regions of Titan, namely the northern polar region, the mid-latitudes, equatorial latitudes, and south pole. There will be little mention of specific points of interest (such as Ontario Lacus and Xanadu), instead they will be saved for the subsequent section.

A. Northern Polar Latitudes

The majority of active fluvial networks on Titan have been found in and around the north pole (M. H. Langans, 2012). These networks are typically dendritic and feed into large lacustrine systems (J. W. Miller, 2021). Whereas, the mid-latitudes mostly consist of arid plains, in the areas of strong lacustrine dominance, the fluvial features behave with an abundance of fluid flow (E. R. Stofan, 2007). Several of the observed fluvial valleys in the northern latitudes are believed in fact to be flooded valleys due to an abundance in liquid alkanes (E. R. Stofan, 2007) (J. W. Miller, 2021). Despite this, it is also generally regarded that Titan’s largest and most extensive fluvial networks are found in this region (M. H. Langans, 2012) (Burr, Drummond, Cartwright, Black, & Peron, 2013), this is not to say that all networks present are in fact so extensive. As (Devon M. Burr, Fluvial features on Titan: Insights from morphology and modeling, 2013) notes, in the area surrounding Kraken Mare, the fluvial networks possess very low Shreve magnitudes (such magnitudes were derived from SAR data of limited resolution and as such may miss smaller tributaries). However, (J. W. Miller, 2021) somewhat contests this by stating that many networks which terminate into Kraken Mare may not be visible at the low resolutions provided by Cassini’s SAR. Indeed, it will be difficult to ascertain the true nature of Titan’s lacustrine-dominated fluvial geomorphology until more accurate data can be provided (whether it be through more accurate SAR or direct scans of the surface via optical instrumentation). Despite this, these lower magnitude networks may also be formed due to the presence of “methanifers”, this is noted due to their lack in complex network geometries and the possibility that lacustrine systems may be more reliant on subsurface alkane sinks (E. R. Stofan, 2007) (Devon M. Burr, Fluvial features on Titan: Insights from morphology and modeling, 2013) (M. H. Langans, 2012). This implies that networks that are more distal to their lacustrine terminals tend to be more extensive. Indeed, these distal networks often appear to originate from more rugged terrain, suggesting high amounts of orographic precipitation is supplying them (Richard Cartwright, 2011).

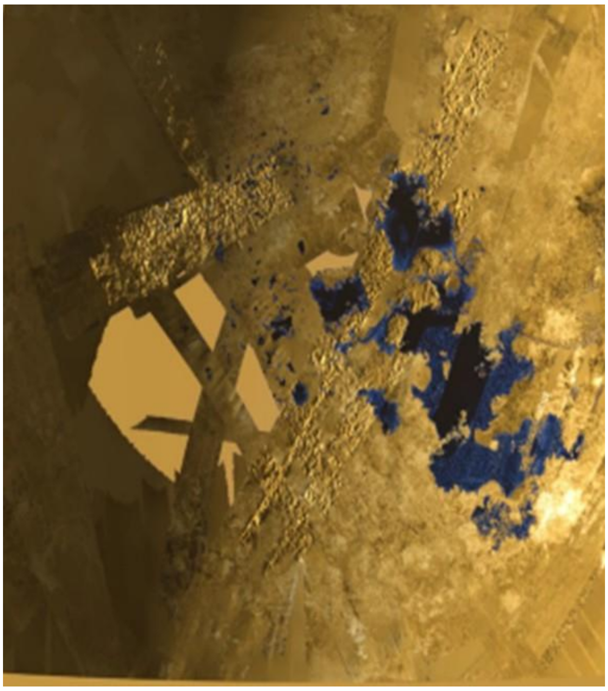


Fig. 1. SAR mappings of the northern lakes of Titan in false colour, courtesy of NASA/JPL-Caltech/ASI/USGS (Jet Propulsion Laboratory (JPL), 2013).

It is difficult to determine the age of these fluvial networks. Due to their complexity, it would initially be indicative that these networks are relatively old (M. H. Langans, 2012), however, due to the aforementioned seasonal fluctuations, it is difficult to determine how much time has passed with these networks undergoing active modification. Furthermore, a general paucity in observed craters on Titan (due in part to fluvial processes eroding said craters) leads to difficulty constraining the evolution of the fluvial channels at the northern latitudes (C. D. Neish, 2016) (M. H. Langans, 2012). While not as pervasive as at other latitudes, tectonic controls are still present at the north pole (M. H. Langans, 2012), while dendritic networks are indicative of advanced age for a fluvial network, tectonic controls often work on a shorter timeframe, which, as (M. H. Langans, 2012) notes, leads to an interesting juxtaposition between the two possibilities for the age of the northern and subsequently all networks on Titan.

Despite this, it is important to note that whereas the majority of networks on Titan have their directionality governed by structural controls or general topography (Burr, Drummond, Cartwright, Black, & Peron, 2013), the northern polar networks are often given their directionality due to lacustrine features (Burr, Drummond, Cartwright, Black, & Peron, 2013) (Richard Cartwright, 2011) (M. H. Langans, 2012).

B. Mid-latitudes

The mid-latitudes of Titan are noted for their aridity, yet they still possess fluvial networks. Indeed, due to their infrequent supply of precipitation, the fluvial networks in this area possess a morphology similar to the wadis found on Earth (M. H. Langans, 2012) (Ralph D. Lorenz e. a., 2008). Perhaps unsurprisingly, seeing as rectangular networks are so evenly distributed across all latitudes on Titan, rectangular networks are also found at Titan's mid-latitudes (Burr, Drummond, Cartwright, Black, & Peron, 2013), however, the mid-latitudes of the northern hemisphere are notably absent in their possession of fluvial networks; of any classification, for that matter (Burr, Drummond, Cartwright, Black, & Peron, 2013).

Despite this, the mid-latitudes are replete with rectangular networks (Burr, Drummond, Cartwright, Black, & Peron, 2013). Of note of course is some clustering of these networks in one particular area, that being Xanadu, which possesses a morphology which would appear to be heavily governed by tectonic processes (Burr, Drummond, Cartwright, Black, & Peron, 2013), with (J. Radebaugh, Regional geomorphology and history of Titan's Xanadu province, 2011) noting that Xanadu is marked by the extensional tectonism that would produce these structural controls. For more details pertaining to Xanadu's fluvial geomorphology see section IV-A. In general, it has been observed that the rectangular networks in the southern area of Xanadu tend to have a further southerly direction of flow and the more northern networks of Xanadu flow further to the north, mainly due to the presence of Menrva Crater (Burr, Drummond, Cartwright, Black, & Peron, 2013).

C. Equatorial Latitudes

The equatorial regions of Titan are most known for their vast sand seas (C. D. Neish, 2016) (Devon M. Burr, Fluvial features on Titan: Insights from morphology and modeling, 2013) (M. H. Langans, 2012) (Birch, Hayes, Howard, Moore, & Radebaugh, 2016) (Ralph D. Lorenz e. a., 2008). However, they also possess what are occasionally referred to as "bland" terrains, marked by a general absence in complex morphology (J. Radebaugh, Regional geomorphology and history of Titan's Xanadu province, 2011). Due to a combination of latitude and distance from sites of active precipitation, there is very little in the way of fluvial geomorphology in the equatorial regions of Titan (M. H. Langans, 2012). Despite this, the DISR data does show an abundance of networks in the vicinity of the Huygens landing site (which landed merely 10.3^{o} south of the equator (European Space Agency (ESA), 2019)), indeed (M. H. Langans, 2012) notes that directly surrounding the landing site there would appear to be several radar-dark networks which may feed into a dry lakebed. However, apart from the area surrounding the Huygens landing site, the equator is generally covered in sand seas made from ice sands and possibly organic compounds (R.D Lorenz, 2006). These sand seas do not appear to possess any fluvial geomorphology, however, this is not to say that ancient fluvial networks are not lying under the equatorial dunes, as (M. H. Langans, 2012) notes.

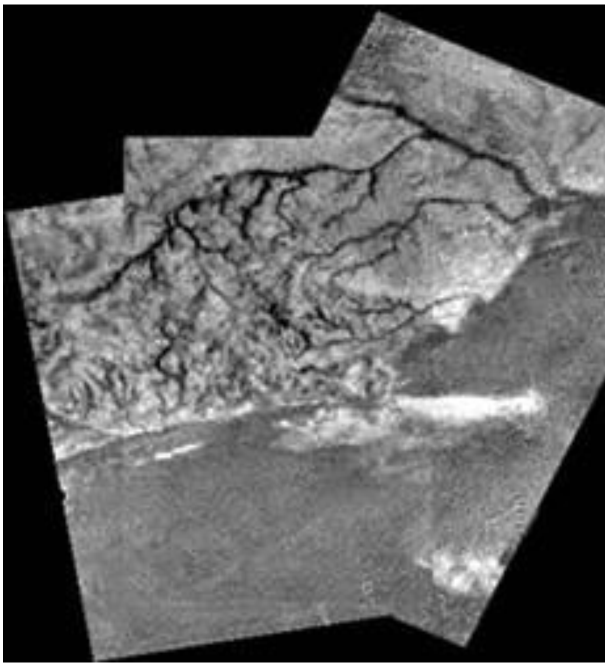


Fig. 2. DISR image of fluvial networks observed during Huygens' descent. Original image (centre) courtesy of NASA/JPL/ESA/University of Arizona (Jet Propulsion Laboratory (JPL), 2005). These are the aforementioned radar-dark networks which (M. H. Langans, 2012) discusses.

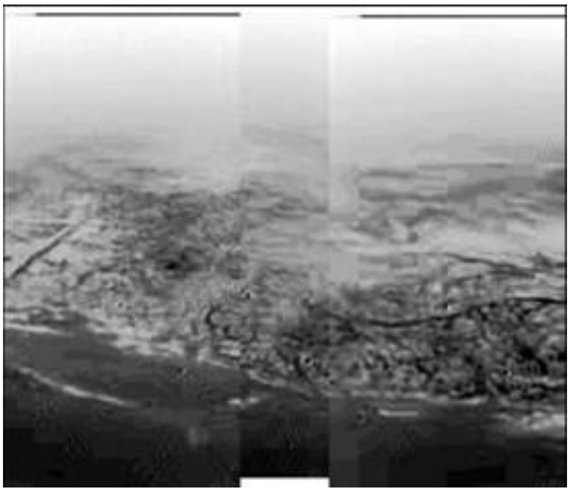


Fig. 3. Mosaic of images produced by DISR, courtesy of NASA/JPL/ESA/University of Arizona (Jet Propulsion Laboratory (JPL), 2005). Here, several putative fluvial networks with radar-dark tones are visible.

Indeed, such hypothetical networks, along with those observed in the DISR data, were likely formed during the rare rainstorms (C. D. Neish, 2016) (M. H. Langans, 2012), the precipitation of such storms was likely directed thanks to orographic rainfall from the equatorial mountains (James W. Barnes, Near-infrared spectral mapping of Titan's mountains and channels, 2007). At least one such storm has been observed in the equatorial band (E.P. Turtle, 2011). (Birch, Hayes, Howard, Moore, & Radebaugh, 2016) notes that the sand seas are likely transport-limited and as such any mechanism that would act to prevent in-fill of fluvial networks is likely outpaced by the weathering of the surrounding terrain. Due to this, any nascent networks formed during the flood events, would likely be rendered inert, or at least severely hampered by the time of the next rainstorm.

D. Southern Polar Latitudes

Perhaps unsurprisingly, Titan's south pole is dominated by fluvial and lacustrine geomorphology, much like the north pole (Giuseppe Mitri, 2007). Baring Ontario Lacus, the southern latitudes generally are less mapped and to a lower resolution than their northern counterparts (J. W. Miller, 2021). Despite this, a clear picture regarding portions of the south pole's fluvial geomorphology can be ascertained.

Whereas the northern polar latitudes of Titan are noted for their dendritic networks which feed into large alkane lakes, the networks in the south pole tend to be more rectangular and are spread across the region with little evidence for lacustrine directional control (Burr, Drummond, Cartwright, Black, & Peron, 2013) (J. W. Miller, 2021).

Directly at and around the south pole there is a current presence of liquid alkanes, although it is smaller in quantity compared to the north pole (S.P.D. Birch, 2018). However, due primarily to the aforementioned seasonal shifts, it would appear that the majority of lakebeds in the southern polar region are dry (J. W. Miller, 2021) (S.P.D. Birch, 2018), this presents an interesting issue in terms of fluvial identification as any dry river networks will appear bright due to the presence of radar-bright (M. H. Langans, 2012) sediments that would have originally been deposited further down or would be covered over by the flowing liquid alkanes, as such, it may be difficult to distinguish between terrain that is fluvial in origin and that which is not (J. W. Miller, 2021).

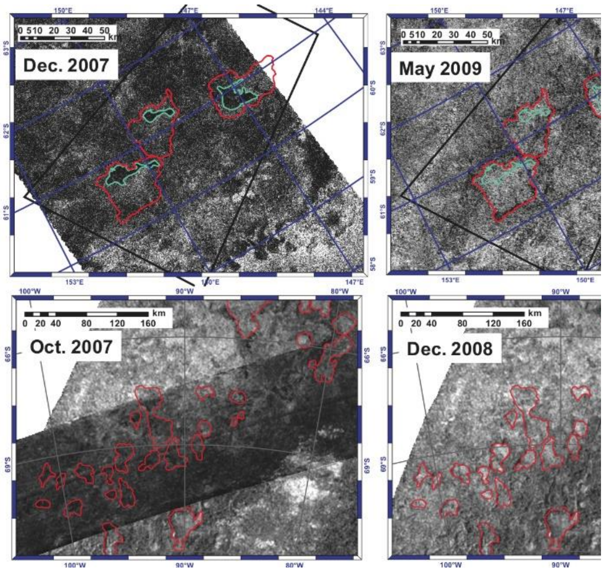


Fig. 4. SAR mapping of some of the lakes of the southern polar region. Courtesy of NASA/JPL-Caltech/ASI (Jet Propulsion Laboratory (JPL), 2009). NASA notes that these lakes were initially recorded in October of 2007 (as marked by the red borders which show where the dry lakebeds were before mapping and the blue borders in the later series of images marking where liquid alkanes had been observed), have since receded with the difference in brightness between the space inside and outside the blue borders being indicative of the lakes loosing significant quantities of liquid alkanes to evaporation) (Jet Propulsion Laboratory (JPL), 2009).

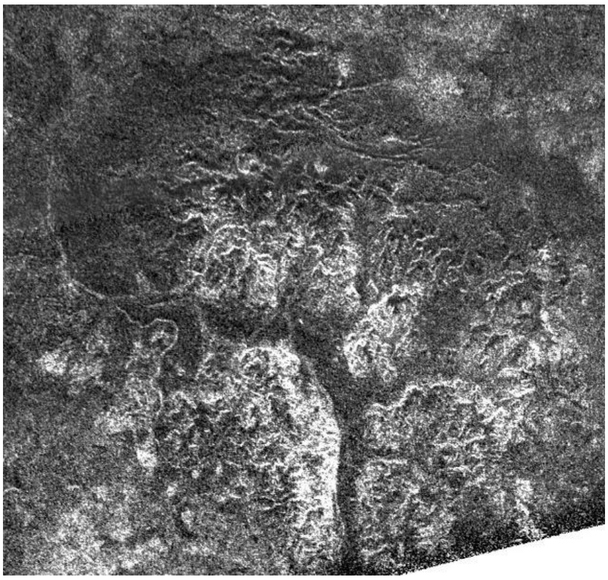


Fig. 5. SAR mapping of a series of fluvial features in Titan’s southern polar region, courtesy of NASA/JPL-Caltech/ASI (Jet Propulsion Laboratory (JPL), 2009). Note the presence of channels which are radar-bright (coarser sediments (M. H. Langans, 2012)) towards the left of the image, and those which are darker towards the top of the image (finer sediments, although likely not undergoing active alkane flow (Jet Propulsion Laboratory (JPL), 2009)).

As for the slightly lower latitudes, there is a strong degree of dominance from Xanadu (J. W. Miller, 2021) (Ontario Lacus would still be considered to be part of the polar region itself), however, it is not the sole source of fluvial geomorphology in this area. Despite, Xanadu being one of the largest relief structures on Titan, let alone in the southern hemisphere, there are several observed fluvial channels which are driven by high relief that are independent of Xanadu (J. W. Miller, 2021).

While the geomorphology of the southern polar fluvial networks bears moderate similarity to those of the north pole, their dimensional constraints are significantly different. (J. W. Miller, 2021) notes that the northern polar networks have an average drainage area of 300Km^2, whereas the southern polar networks have an average drainage density of 700Km^2. It is important to note that lacustrine features tend to produce “stubbier” networks (M. G. Tomasko, 2005), as such the southern polar networks, which tend to not be tied to any observed lacustrine features, should have larger drainage areas (J. W. Miller, 2021), as the data show.

IV. Titanian Fluvial Landforms

The aim of this section is to analyse the current paradigm surrounding specific regions and putative fluvial morphological features present on Titan. While not a particularly exhaustive list, it should aim to further paint a reliable picture of Titan’s fluvial geomorphology as a whole.

A. Xanadu

As far as fluvial geomorphology is concerned, Xanadu is by far one of the most diverse and fascinating regions of Titan. Possessing some of the longest networks observed on Titan (M. H. Langans, 2012), along with being surrounded by diverse landforms such as sand seas to the west, lowlands to the north and east, and flow structures to the south (J. Radebaugh, Regional geomorphology and history of Titan’s Xanadu province, 2011). This, coupled with Xanadu’s own internal complexity, leads to necessary subdivision of Xanadu into regions which (J. Radebaugh, Regional geomorphology and history of Titan’s Xanadu province, 2011) notes as the “Western Drainages”, “Southern Flow Complexes”, the “Middle Rugged Terrains”, and the “Eastern Belts”. For the sake of commonality, not only will I use these terms, but I will also abide by the same boundaries for Xanadu that were used in the aforementioned paper, this is particularly of note for the regions of Hotei Regio and Tui Regio.

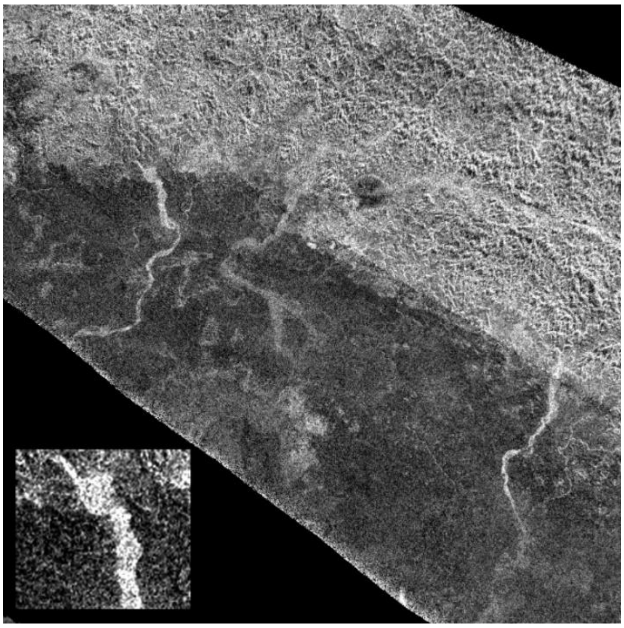


Fig. 6. A collection of fluvial channels at Xanadu. Courtesy of NASA/JPL-Caltech/ASI (Jet Propulsion Laboratory (JPL), 2008).

1) Western Drainages: The Western Drainages are noteworthy for possessing both a limited relief and a supposedly similar elevation to neighbouring Shangri-La (a vast sand sea) (J. Radebaugh, Regional geomorphology and history of Titan's Xanadu province, 2011). The primary networks in this region are observed to be dendritic and flow southwards, however due to the limited relief these networks possess a very shallow slope (Devon M. Burr, Fluvial network analysis on Titan: Evidence for subsurface structures and west-to-east wind flow, southwestern Xanadu, 20009) (J. Radebaugh, Regional geomorphology and history of Titan's Xanadu province, 2011). To the east, as we approach the Middle Rugged Terrains, we see some of Titan's longest networks, with (J. Radebaugh, Regional geomorphology and history of Titan's Xanadu province, 2011) noting that some reach as much as 200Km in length. These networks are believed to be pluvial in origin and are also rectangular, suggesting strong tectonic control (Ralph D. Lorenz e. a., 2008) (Devon M. Burr, Fluvial network analysis on Titan: Evidence for subsurface structures and west-to-east wind flow, southwestern Xanadu, 20009). This area is unique for being one of the few non-polar morphological features to present with both dendritic and rectangular channel morphology.

2) Southern Flow Complexes: To an extent, the Southern Flow Complexes are an extension of the Western Drainages. The extensive networks which are believed to originate in the Western Drainages terminate in the Southern Flow Complexes, indeed, such termini are located towards the northwest, leaving the rest of the area to be covered in diverse landforms (J. Radebaugh, Regional geomorphology and history of Titan's Xanadu province, 2011). Further south, the carved terrain appears fade away to bland lowland, but the remaining networks are also rectangular in nature (J. Radebaugh, Regional geomorphology and history of Titan's Xanadu province, 2011) (Devon M. Burr, Fluvial network analysis on Titan: Evidence for subsurface structures and west-to-east wind flow, southwestern Xanadu, 20009). There would appear to be several depositional structures such as alluvial fans and deltas in the Southern Flow Complexes (Jeffrey M. Moore, 2010), this further reinforces the belief that we are looking at the termini for large fluvial networks originating further north. The lobate flows observed across this area, but particularly in the regions of Hotei Regio and Tui Regio, are believed to be cryovolcanic in origin (S. Wall, Cassini RADAR images at Hotei Arcus and western Xanadu, Titan: Evidence for geologically recent cryovolcanic activity, 2009), however, this is contested with the observation by (Jeffrey M. Moore, 2010), in part due to the presence of putative fluvial networks at both regions.

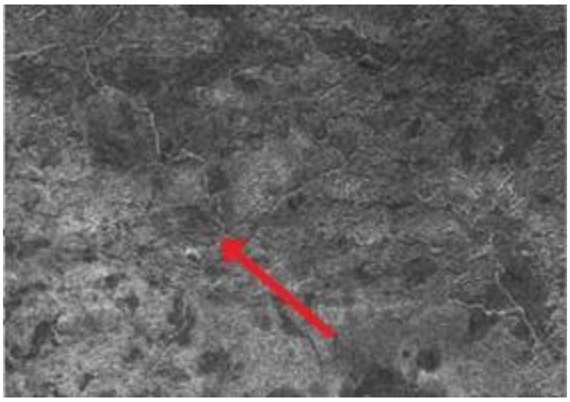


Fig. 7. SAR Mapping of the Southern Flow Complexes, courtesy of NASA/JPL-Caltech/ASI (Jet Propulsion Laboratory (JPL), 2006). (Devon M. Burr, Fluvial network analysis on Titan: Evidence for subsurface structures and west-to-east wind flow, southwestern Xanadu, 20009) notes the presence of rectangular networks in this region (noted here with the red arrow).

3) Middle Rugged Terrains: The Middle Rugged Terrains are noteworthy for possessing some of the highest peaks (and thus highest reliefs) across all of Titan, standing in some places at around 2Km (J. Radebaugh, Mountains on Titan observed by Cassini Radar, 2007). Interestingly, the mountain valleys themselves contain radar-dark material, (J. Radebaugh, Regional geomorphology and history of Titan's Xanadu province, 2011) notes that they may be fine sediments eroded directly from the mountains or were deposited by fluvial or lacustrine processes, this is also not dissimilar to the processes acting on Italy's Po Valley. Due to the presence of mountains in this area, it is clear that the centre of Xanadu is dominated by tectonic processes and thus, structural controls are the primary driver of fluvial geomorphology, hence the observed rectangular networks in this region (J. Radebaugh, Regional geomorphology and history of Titan's Xanadu province, 2011). Indeed, if the sediments observed in the valleys do originate from the adjacent mountains, this would further support the belief that Titan had more precipitation in the recent past (J. Radebaugh, Regional geomorphology and history of Titan's Xanadu province, 2011).

Of note is the presence of fluvial structures emblematic of terrestrial drowned valleys (J. Radebaugh, Regional geomorphology and history of Titan's Xanadu province, 2011). This is of interest as such structures are typically only found in the polar regions of Titan and are indicative of intense fluid flow and subsequent fluvial geomorphology (E. R. Stofan, 2007). Furthermore, both (J. Radebaugh, Regional geomorphology and history of Titan's Xanadu province, 2011) (J. Radebaugh, Mountains on Titan observed by Cassini Radar, 2007) note that these mountains are of similar morphology to the eroded compressional mountains of the Himalayas on Earth.

4) Eastern Belts: The Eastern Belts are in many ways similar to the Middle Rugged Terrains, possessing significant mountainous terrain and similar radar-dark sediments along the eastern boundary (J. Radebaugh, Regional geomorphology and history of Titan's Xanadu province, 2011). Interestingly, the networks present are noted by (J. Radebaugh, Regional geomorphology and history of Titan's Xanadu province, 2011) to be similar to those observed by (Devon M. Burr, Fluvial network analysis on Titan: Evidence for subsurface structures and west-to-east wind flow, southwestern Xanadu, 20009), indeed, the networks observed both here and in the Western Drainages are typically rectangular or trellis in morphology, however the networks in the Eastern Belts are sparser and are more poorly linked (J. Radebaugh, Regional geomorphology and history of Titan's Xanadu province, 2011). This in turn implies that all of Xanadu has been governed by a certain east-west tectonic folding, producing the observed mountains and, more crucially, structurally controlled networks (J. Radebaugh, Regional geomorphology and history of Titan's Xanadu province, 2011). Of course it is important to note that the networks observed in the Eastern Belts flow southerly, much like those of the Western Drainages and Southern Flow Complexes (J. Radebaugh, Regional geomorphology and history of Titan's Xanadu province, 2011), as would be expected, seeing as Xanadu is believed to be an ancient elevation which has since sunk in a southerly inclination (J. Radebaugh, Regional geomorphology and history of Titan's Xanadu province, 2011).

B. Ontario Lacus

Ontario Lacus is noteworthy for being one of the only observed lacustrine systems which is currently active in the southern polar region (S. Wall, Active shoreline of Ontario Lacus, Titan: A morphological study of the lake and its surroundings, 2010). Furthermore, it is one of the most extensively mapped lacustrine features on Titan, as such it is important to note the surrounding fluvial features. Perhaps unsurprisingly, the most dominant fluvial features here are flooded river valleys, as tends to be the case surrounding the active lacustrine systems to the north (E. R. Stofan, 2007), interestingly, there also appear to be a wealth of alluvial fans and deltas observed here (S. Wall, Active shoreline of Ontario Lacus, Titan: A morphological study of the lake and its surroundings, 2010).

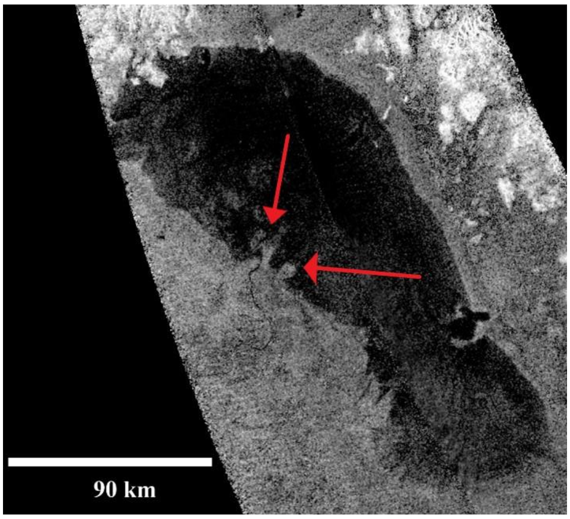
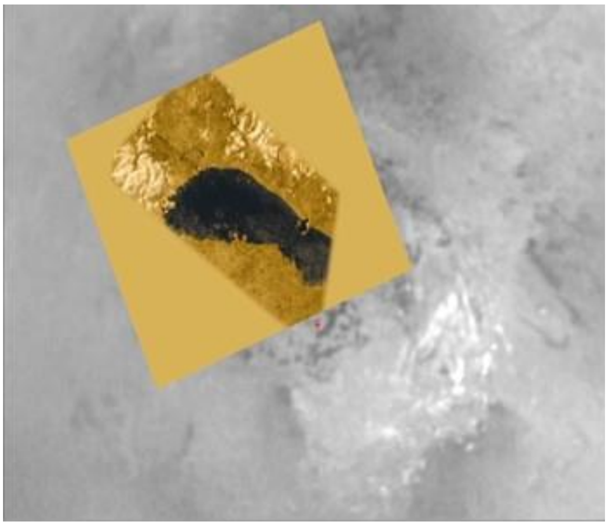


Fig. 8. SAR mapping of Ontario Lacus, towards the centre of the leftmost shoreline several lobate structures can be identified (as noted by the arrows), (S. Wall, Active shoreline of Ontario Lacus, Titan: A morphological study of the lake and its surroundings, 2010) notes that these are likely deltas produced by the switching of distributary networks and are possibly of a similar morphology to those found at the Semliki River at the south of Lake Albert. Courtesy of NASA/JPL-Caltech/ASI (Jet Propulsion Laboratory (JPL), 2010)



Fig, 9. False colour image of Ontario Lacus and surrounding terrain, note the presence of fluvial features. Courtesy of NASA/JPL-Caltech/ASI (Jet Propulsion Laboratory (JPL), 2010).

It is important to note that (S. Wall, Active shoreline of Ontario Lacus, Titan: A morphological study of the lake and its surroundings, 2010) observed a 10Km shoreline in the five years between the infrared and SAR mapping of Ontario Lacus, this further reinforces the notion of seasonal procession and recession of liquid alkanes from a given pole. At the time that (S. Wall, Active shoreline of Ontario Lacus, Titan: A morphological study of the lake and its surroundings, 2010) was published, Titan was transitioning from a south-polar summer to autumn (M. H. Langans, 2012), hence the recession of liquid alkanes was still on-going.

C. The Huygens Landing Site (HLS)

The data acquired from the Huygens Landing Site has been invaluable in painting an accurate picture of Titan's recently active fluvial geomorphology, by providing higher resolution mapping and data regarding fluvial mechanics directly. Unfortunately, only half of the images taken with the DISR were successfully transmitted to Cassini (M. G. Tomasko, 2005), limiting the depth of study for this region.

Of particular note is that the DISR data indicates that not only are dendritic (Laurence A. Soderblom, 2007) and rectangular (Burr, Drummond, Cartwright, Black, & Peron, 2013) networks present at the HLS, but also "stubby" networks, which were possibly produced by sapping (M. G. Tomasko, 2005). While there is some consensus that these stubby networks may have formed due to sapping, (Devon M. Burr, Fluvial features on Titan: Insights from morphology and modeling, 2013) (M. G. Tomasko, 2005) (Laurence A. Soderblom, 2007), (M. H. Langans, 2012) notes that only one such network has been positively identified as likely being a network, at least partially, produced by sapping due to the presence of an "amphitheatre-shaped" (M. H. Langans, 2012) head. Despite this, it is clear that the HLS and its surroundings contains a very diverse and distinct fluvial geomorphology. Furthermore, not only do we see diverse fluvial geomorphology, but we also observe morphology not seen anywhere else on Titan, principally due to the significant increase in resolution (Cassini's SAR has an approximate resolution of 350m-1,700m (National Aeronautics and Space Administration (NASA), 2018), whereas the DISR has a maximum resolution of 20m (Williams, 2005)).

As is the case for the rest of Titan, to the north of the HLS rugged terrains have been observed, from which orographic precipitation would occur (Laurence A. Soderblom, 2007). To the east of the HLS, there would appear to be scour with a flow direction of west-east, indicating that fine sediment was carried by liquid alkanes moving with a high flow velocity (likely caused by the relatively high slope in the area of 30º (M. G. Tomasko, 2005)) (Laurence A. Soderblom, 2007). In the regions governed by primarily by structural control, (Laurence A. Soderblom, 2007) notes that bright material may have been produced by cryovolcanism, such cryovolcanism is believed to have weakened the surrounding terrain, allowing for rectangular networks to form, this would align with the general consensus as to the origin of the rectangular networks on Titan; that being that they formed due to weaknesses in the bedrock produced by tectonism (M. H. Langans, 2012). The plains surrounding the HLS would appear to have networks which flow downwards from one level to another and from west-north-west to east-south-east, furthermore, this site is of interest as it is strewn with rounded cobbles (Laurence A. Soderblom, 2007).

Indeed, it is believed that Huygens landed in the basin of a recently dried lakebed (M. G. Tomasko, 2005) (M. H. Langans, 2012), this is supported by the presence of dark terrains (and thus likely fine sediment that was deposited as the lakebed acts as a terminal for any fluvial networks connected to it, similar to the northern area of Xanadu's Southern Flow Complexes (J.

Radebaugh, Regional geomorphology and history of Titan's Xanadu province, 2011)) and rounded cobbles directly adjacent to the HLS (Laurence A. Soderblom, 2007). As for the cobbles, (M. G. Tomasko, 2005) notes that they appear to on average range from 50-150mm in diameter, implying that larger rocks and stones would have been deposited further upstream, with most smaller pebbles being carried further into the lake.

Fig. 10. DISR image of the surface of Titan, courtesy of NASA/JPL/ESA/University of Arizona (Jet Propulsion Laboratory (JPL), 2005). Note the presence of the aforementioned rounded cobbles.

Interestingly, (Giuseppe Mitri, 2007) notes that if the soil surrounding Huygens is not particularly porous, then the most recent pluvial event was likely on the order of several years to several decades ago, this would again fit the consensus of Titan's infrequent flood events (furthermore, the presence of sandbars that (Laurence A. Soderblom, 2007) observed, are indicative of flood events). Indeed, the HLS is a noteworthy as it likely reflects the general condition of the regions of the equator not defined by sand seas, as noted by the relative proximity of the HLS to them (some 30Km, according to (Laurence A. Soderblom, 2007)).

D. The Alluvial Fans and Deltas of Titan

Alluvial fans and deltas are perhaps some of the most interesting landforms on Titan as they allow us to get a sense of not only the state of the rivers that they are connected to but can also tell us about how the fluvial system is influencing the surrounding terrain in more subtle ways, rather than directly studying the typical fluvial geomorphology of a region.

On Titan, fluvial deltas are noted by (S. Wall, Active shoreline of Ontario Lacus, Titan: A morphological study of the lake and its surroundings, 2010) to be roughly two orders of magnitude smaller than their terrestrial counterparts, indeed, this significant decrease in area is attributed to low fluid velocities, sediment carrying capacity and being in supply-limited regime. However, this is based on the sole delta directly observed, having been found at Ontario Lacus (S. Wall, Active shoreline of Ontario Lacus, Titan: A morphological study of the lake and its surroundings, 2010), with (Jeffrey M. Moore, 2010) noting the possible presence of more on Titan. Unfortunately, due to the limits of the SAR mapping, it will continue to prove difficult to find further evidence of deltas and their mechanisms on Titan, with (M. H. Langans, 2012) noting a particular absence of deltas in the regions assessed. (Piotr P. Witek, 2015) notes that while only one delta has been directly observed so far on Titan, it is very likely that more will be found, owing to the more efficient erosion present on Titan, according to their calculations.

Whereas there has been only one delta believed to have been directly observed so far, many alluvial fans have been observed so far (A. Le Gall, 2010) (Birch, Hayes, Howard, Moore, & Radebaugh, 2016) (Devon M. Burr, Fluvial features on Titan: Insights from morphology and modeling, 2013) (M. H. Langans, 2012) (S. Wall, Active shoreline of Ontario Lacus, Titan: A morphological study of the lake and its surroundings, 2010) (J. Radebaugh, Regional geomorphology and history of Titan's Xanadu province, 2011) (Ralph D. Lorenz e. a., 2008) (J. W. Miller, 2021). These fans have been found in every region bar the equatorial sand seas (with only a few alluvial fans being observed near the equator at Xanadu) (Birch, Hayes, Howard, Moore, & Radebaugh, 2016). In general, Titanian alluvial fans appear radar-bright, although dark fans are of course possible due to the presence of finer sediment in more recently active fluvial systems. (Birch, Hayes, Howard, Moore, & Radebaugh, 2016) notes that Titanian fans have the potential to be significantly larger than those found on both Earth and Mars, primarily due to Titan's lower gravity. However, (Birch, Hayes, Howard, Moore, & Radebaugh, 2016) also notes that the absence of any fans currently observed being so large is a possible indicator that Titan has an environment that is at present too transport-limited to permit such fan formation (owed in part to the fact that Titan is particularly arid environment at present (Birch, Hayes, Howard, Moore, & Radebaugh, 2016) (M. H. Langans, 2012)). Interestingly, many of the alluvial fans resemble terrestrial bajadas (Birch, Hayes, Howard, Moore, & Radebaugh, 2016), perhaps this is unsurprising as bajadas on Earth are usually found in arid environments where fluvial activity was more prolific in the past.

The alluvial fans on Titan (particularly the brighter specimens) are important to note as they act as relics of previously active fluvial activity (Birch, Hayes, Howard, Moore, & Radebaugh, 2016) and can better inform us as to the characteristics of the fluvial systems that formed them (for example, the presence of an alluvial fan in or around a crater can roughly inform as to the age of the crater, with younger craters likely not undergoing much in the way of fluvial modification). Despite this, certain erosive processes may be sufficient to remove any evidence of alluvial fans in a given area. (Birch, Hayes, Howard, Moore, & Radebaugh, 2016) notes that it is possible that during periods where Titan's equator has been more humid (either due to rainstorms or a more alkane-rich past), there may have been alluvial fans in the areas where equatorial sand seas are now observed. Furthermore, due to the favourable conditions for aeolian modification to occur (R.D. Lorenz, 2006), it is possible that the alluvial fans are modified faster than the fluvial processes that infrequent rainstorms induce can liberate them from the encroaching sand seas.

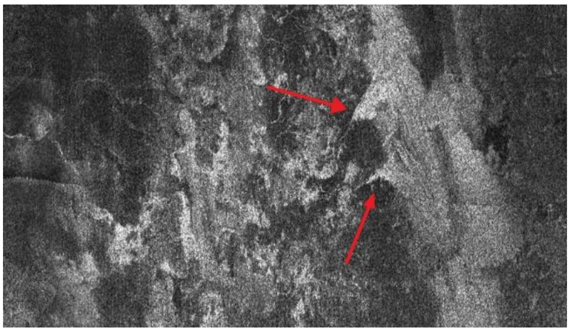


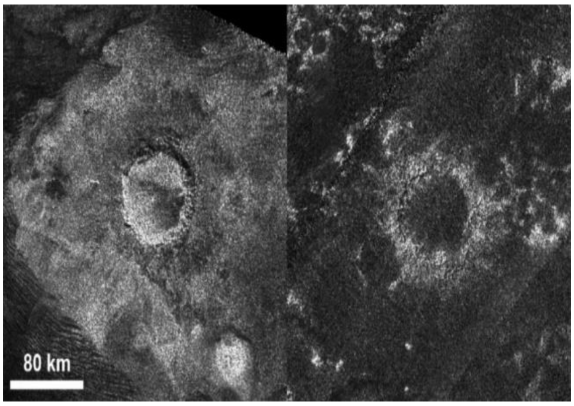
Fig. 11.The first SAR mapping of Titan. (A. Le Gall, 2010) notes the presence of two putative alluvial fans (labelled by the two red arrows). Courtesy of NASA/JPL-Caltech/ASI (Jet Propulsion Laboratory (JPL), 2004). Due to the presence of crenulated terrain connected to the start of the fans, it is reasonable to assume that this terrain is mountainous and that these alluvial fans are in fact bajadas.

E. Supplementary Geomorphology

While there are many landforms directly produced by fluvial activity, there are many which are only formed indirectly. Such forms sit at the edge of intent for this review, but it is nevertheless important for them to be covered. The analysis of such landforms is the aim of this section.

1) Fluvial erosion and modification of Titan's craters: The general absence of craters on Titan (M. H. Langans, 2012) is noted to be due to both Titan's atmosphere (where, much like on Earth, only larger asteroids will survive the process of re-entry and will thus produce impact craters) (Birch, Hayes, Howard, Moore, & Radebaugh, 2016) and the active erosive processes on Titan (C. D. Neish, 2016). Indeed, fluvial modification is the predominant mechanism for crater modification in the more humid environments of Titan, (C. D. Neish, 2016) notes that fluvial processes on Titan work to degrade the walls and peaks of craters, while also permitting the infilling of sediments into the crater. Furthermore, while fluvial weathering and infilling may be more prominent in the humid regions of Titan, in and around the equatorial regions (where most of Titan's craters have been observed (C. D. Neish, 2016) (J. Radebaugh, Regional geomorphology and history of Titan's Xanadu province, 2011)) fluvial modification only acts to prepare the crater for infilling due to primarily aeolian processes, this indeed makes sense as fluvial activity is driven by infrequent rainstorms in the equatorial bands (C. D. Neish, 2016).

Fig. 12 (Below). Composition of several images from Cassini of the possibly younger Sinlap Crater (left) and the older Soi Crater (right), which has likely undergone significant fluvial modification. Courtesy of NASA/JPL-Caltech/ASI/GSFC (Jet Propulsion Laboratory (JPL), 2013).



(C. D. Neish, 2016) notes that in the equatorial regions, the uniform nature of the infilling, paired with the general absence of craters to the north, is indicative that aeolian processes are dominant for both weathering and erosion, this is similar to the mechanisms which potential drive the cloaking of alluvial fans beneath sand seas (Birch, Hayes, Howard, Moore, & Radebaugh, 2016).

It is important to note that some craters influence the directionality of fluvial networks on Titan, particularly, Menrva Crater, near Xanadu, causes networks to flow northwards (Burr, Drummond, Cartwright, Black, & Peron, 2013), two of these networks are over 200Km, with one of them possibly breaching into Menrva Crater, leaving its western rim more degraded than the rest of the crater rim (Ralph D. Lorenz e. a., 2008).

2) Mountainous fluvial modification: The mountainous terrain on Titan acts to constrain and promote fluvial activity. Precipitation is the main source of liquid alkanes for Titan's rivers (M. H. Langans, 2012). In turn, orographic rainfall is one of the primary drivers of fluvial directionality on Titan (M. H. Langans, 2012). As such, the mountains of Titan themselves are modified by fluvial processes, forming valleys which oftentimes contain sediment which likely originates from the mountains themselves (J. Radebaugh, Regional geomorphology and history of Titan's Xanadu province, 2011), leading to the presence of heavily dissected mountains (M. H. Langans, 2012). (M. H. Langans, 2012) notes that it is possible that the mountainous terrain may be more susceptible to fluvial erosion than other terrains on Titan.

3) Titanian Flood Plains: Owing to the violent and ephemeral nature of Titanian storms, most non-polar fluvial networks undergo flooding when they receive precipitation (M. G. Tomasko, 2005). Such flooding can often form flood plains, (M. H. Langans, 2012) notes that these flood plains are the result of highly erratic flow rates for fluvial networks, with the plains themselves oftentimes being composed of fine, dark sediment, which stand out clearly against the coarser surrounding terrain. (M. H. Langans, 2012) goes on to note that these flood plains are the result of a network not having a strong drainage to feed into, such as a basin or lake.

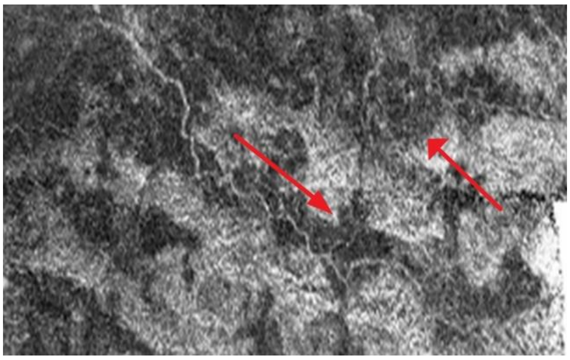


Fig. 13. A SAR mapping of southern Xanadu, note the radar-dark structures (annotated with the red arrows), which (M. H. Langans, 2012) states are putative flood plains. Courtesy of NASA/JPL-Caltech/ASI (Jet Propulsion Laboratory (JPL), 06).

V. Conclusion

The fluvial environment on Titan can be described in some sense as being "exotically Earth-like", this is due to the clear presence of landforms similar to landforms found in arid regions on Earth, but with vastly different operating parameters such as gravity, chemistry, temperature, density, etc. With this in mind, it is still important to note that while the fluvial geomorphology may be similar, the morphogenesis is rather distinct. Earth enjoys an abundance of liquid water, across all latitudes (bar the modern-day north and south poles) and all seasons. In comparison to Titan, which lacks oceans, only maintains considerable bodies of liquid alkanes at its poles (E. R. Stofan, 2007) and only allows for said bodies to grow during a polar winter (M. H. Langans, 2012). Furthermore, whereas on Earth we observe almost every latitude having at least some active fluvial activity, Titan only allows the lower latitudes to receive fluvial activity during infrequent storms, or an ever-present mild drizzle.

Despite this, it is clear that there is much to be learned about how Titan's fluvial geomorphology and morphogenesis works on longer timescales, while some evidence of seasonal humidity cycles have been observed at Ontario Lacus (S. Wall, Active shoreline of Ontario Lacus, Titan: A morphological study of the lake and its surroundings, 2010), the extent to which seasonal variation impacts liquid alkane reservoirs is not fully understood. Furthermore, while sapping and thus subsurface "methanifers" (E. R. Stofan, 2007) are believed to play an important part in Titan's fluvial geomorphology, they are neither well understood nor well-observed (Devon M. Burr, Fluvial features on Titan: Insights from morphology and modeling, 2013), long-term orbital surveys, ideally across the timescale of multiple seasonal cycles and further surface analyses, particularly in regions where "methanifers" are believed to be more prevalent, will help immensely in solving some of these mysteries.

In summary, while Titan is in many ways a world unlike any other, seeing as it is the only moon in the solar system with a substantial atmosphere and operates on an entirely different chemical regime to Earth and Mars, it is incredible how similar it is in terms of fluvial morphogenesis, geomorphology, and fluvial mechanisms. The equifinality between terrestrial and Titanian fluvial processes is rather perplexing and invites great scientific curiosity as to how two entirely different physical and chemical systems can form such similar landforms to each other. Indeed, one must wonder that if two systems as distinct as Titan and Earth may produce such similarities, can the same be said for exoplanets and exomoons?

Furthermore, while this review has definitely raised questions regarding the sources and mechanisms behind Titan's fluvial geomorphology and morphogenesis, it has also clearly stated that some components would appear to be nearly certain. Of highest note would be the arid nature of Titan's non-polar latitudes (M. H. Langans, 2012), along with the seasonality of the poles' fluvial and lacustrine features (E. R. Stofan, 2007).

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